REPORT OF CONSTELLATION-X MINI-WORKSHOP ON SUPERNOVA REMNANTS AND THE DIFFUSE INTERSTELLAR MEDIUM

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I. SUPERNOVA REMNANTS

The capabilities of Constellation-X will open a new window into the physics of supernova (SN) explosions through a dramatic improvement in the quality of the observations of young, ejecta-dominated supernova remnants (SNRs). The high spatial and spectral resolution of Constellation-X will enable determination of the composition, ionization state and velocity of the material throughout the SNR to build a complete model for the structure of the shocked ejecta and the ambient medium. This has an enormous potential to constrain both the physics of supernova explosions and the details of the pre-supernova evolution of the progenitor systems for both core collapse and thermonuclear supernovae. Constellation-X will also enhance our understanding of other aspects of supernova remnants, such as the acceleration of cosmic rays at shock fronts and pulsars and their wind nebulae.

Core Collapse

Constellation-X observations of core-collapse SNRs, particularly young remnants, will unveil new information about the core-collapse process by revealing the distribution and dynamics of nucleosynthesis products formed during the explosion. Other Constellation-X studies include detailed investigations of the early evolution of SNRs, unveiling unshocked Fe, and measuring the total mass of Fe in SN ejecta.

A prime target for studies of core collapse supernovae is the well-studied Cassiopeia A (Cas A), because it is the brightest X-ray remnant with emission dominated by Si and Fe ejecta. The X-ray emission from Cas A is spatially complex, showing structure on scales from the remnant's full ~ 3' extent to knots and filaments <~2" in size (Hughes et al. 2000, Hwang et al. 2000). Ejecta radial velocities of up to ~2000 km s^{-1} have been measured on 20" scales with XMM-Newton (Willingale et al. 2002). Hwang & Laming (2003) and Laming & Hwang (2003) demonstrated that the X-ray emission from Cas A's Si- and Fe-rich ejecta knots can be used to determine the ejecta density profile, explosion asymmetry, and mass coordinate of ejecta structures. However, this previous work has been done at CCD spectral resolution (R <~ 100). While Astro-E2 offers much higher spectral resolution, but it will be unable to study individual, compositionally distinct ejecta knots. Only Constellation-X will enable deeper investigations into the nature of the knots and other complex ejecta structures. *The primary instrumental capability that limits our ability to carry out analysis of these ejecta knots is angular resolution. A goal of 2" is necessary to obtain clean spectra from individual knots in the remnant. While good science could be accomplished with a 5" resolution, our ability to isolate relevant features would be significantly degraded. This analysis would be impossible with angular resolution of 15".*

Constellation-X has the angular resolution and high sensitivity necessary for detailed studies of the unshocked Fe in Cas A. The radioactive nucleus ^{44}Ti is closely connected with the explosive nucleosynthesis of Fe by complete Si burning (α-rich freeze-out). ^{44}Ti decays with a 60-day half-life to ^{44}Sc, then quickly to Ca. The Constellation-X calorimeter will reveal sites of ^{44}Ti production by mapping the inner-shell line radiation of ^{44}Sc at 4.086 and 4.090 keV. In addition Constellation-X will allow us to observe and study emission from other, less abundant species in the hot ejecta, including phosphorus, potassium, titanium (P, K, Ti) and the rest of the Fe group elements (V, Cr, Mn, Co and Ni). Ti and the Fe group elements in particular are sensitive to the poorly understood final mass cut between the ejecta and the forming neutron star (Woosley & Weaver 1995).

In addition, the nuclear de-excitation lines associated with both decay products of ^{44}Ti have been detected in hard X-rays and γ-rays in Cas A (Vink et al. 2001, Iyudin et al. 1994). ^{44}Ti is an important estimator of the total Fe mass, and models predict that both core-collapse and thermonuclear explosions produce ^{44}Ti in varying amounts. However, these lines have not been convincingly detected in other remnants. If the HXT's energy response were extended to 100 keV, Constellation-X would be able to detect the two lines associated with ^{44}Sc at 67.90 and 78.4 keV.

Another exciting target for core collapse studies is SN 1987A. SN 1987A has given astronomers a unique opportunity to witness the birth of a supernova remnant. In recent years, its X-ray luminosity has increased rapidly as the forward shock crashes into the dense inner ring of circumstellar material (Park et al. 2004). The remnant may brighten 10- to 100-fold before Constellation-X launches (McCray, private communication 2004). The reverse shock has begun to propagate through the ejecta and is now being observed in high-velocity H-emission (Michael et al. 2003). In time heavier elements will begin to cross the reverse shock and reveal the radial structure of the ejecta. The estimated velocities of ejecta crossing the reverse shock range from 5700 km s^{-1} to 6700 km s^{-1} during the 5-year Constellation-X lifetime, while Fe ejecta are expected to reach lower velocities of ~4400 km s^{-1} (McCray 1993).

Thermonuclear Supernovae (SNe Ia) and their Remnants

One of the unsolved problems in SN research is the nature of Type Ia SNe (SN Ia) progenitor systems. One possible progenitor system is a C-O white dwarf accreting H/He-rich gas from a companion, in which case some circumstellar gas should be present when the SN explodes. Early Constellation-X observations of bright SN Ia (preferably before maximum optical brightness ~20 days after ignition) will constrain the progenitor's circumstellar environment. However, circumstellar material (CSM) in a normal SN Ia has yet to be detected. Currently, Chandra can reach a flux limit of $\sim 10^{-15}$ ergs cm^2 s^{-1} (2-10 keV band) in 20 ks. Constellation-X will go an order of magnitude fainter, so will have 3× higher sensitivity to the CSM density. The precise limit depends nearly linearly on how soon after the explosion the SN is observed.

The cosmological importance of SNe Ia have inspired new surveys aimed at detecting early SNe Ia (2 days after the explosion) at distances comparable to the Virgo cluster (~16 Mpc; closer SNe Ia are very rare). Ongoing surveys are projected to discover 1 bright (mag 12-13) early SN Ia per year. *Since time is of critical importance, Constellation-X must be able to observe a target of opportunity SN within 2 days.*

Another issue for SN follow-up studies is the area of sky available for rapid slew. If Constellation-X's slew capability is limited to some fraction of the sky, then the number of targets it could potentially observe drops by that same fraction. With 20% sky coverage over the course of the 5 yr mission, then Constellation-X would have a good chance of targeting one bright SN Ia over its lifetime. *This level of sky coverage (20%) is the absolute minimum that would allow this science to be done.*

The Constellation-X studies on the structure of the shocked ejecta and ambient medium in Type Ia SNe will be instrumental to resolving the current debate over the explosion mechanism and progenitor systems (see Badenes et al., 2003; Badenes & Bravo, 2001). Using Chandra observations of the Tycho SNR as a benchmark (Figure 1), several requirements for Constellation-X arise. While an angular resolution of 10”-15” is adequate for studying the clumpy ejecta emission (based on images and spectra from Hwang et al. 2002), better resolution would help distinguish forward shock emission from ejecta at the remnant's rim. The calorimeter's nominal 2-eV spectral resolution gives a resolution $R = E/\Delta E = 3000$ at the Fe Kα lines. In this region, ~10 bright lines are expected from individual charge states spread over a few hundred eV, so even if the velocity of the shocked ejecta in Tycho is ~3000 km s^{-1}, the kinetic shifts and broadenings should be ~60 eV and line blending should not be a major issue. Finally, a large field-of-view (FOV) is desirable for imaging extended objects; however, even with a small FOV, the large effective area of Constellation-X will allow a spatial scan of the entire extent of Tycho (diameter of 8’) in a reasonable total exposure time (~100 ks).

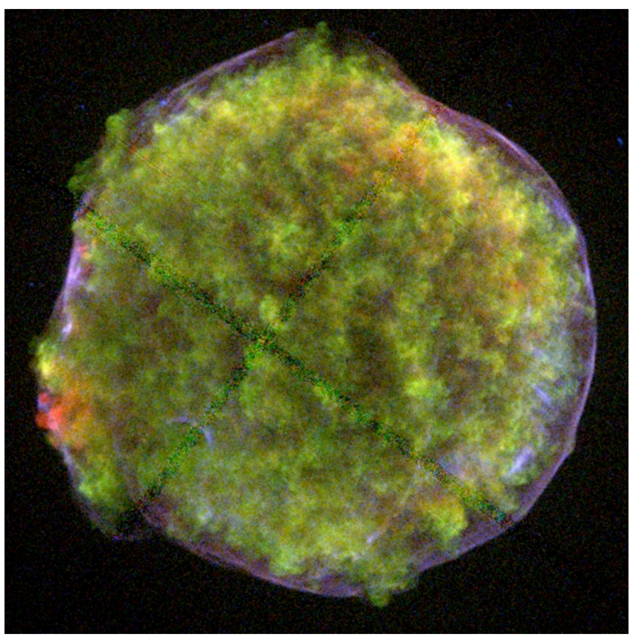


Figure 1: Chandra X-ray image of the Tycho supernova remnant showing Fe-rich ejecta (red features), Si-rich ejecta (green features), and featureless spectra from the forward shock (blue rims).

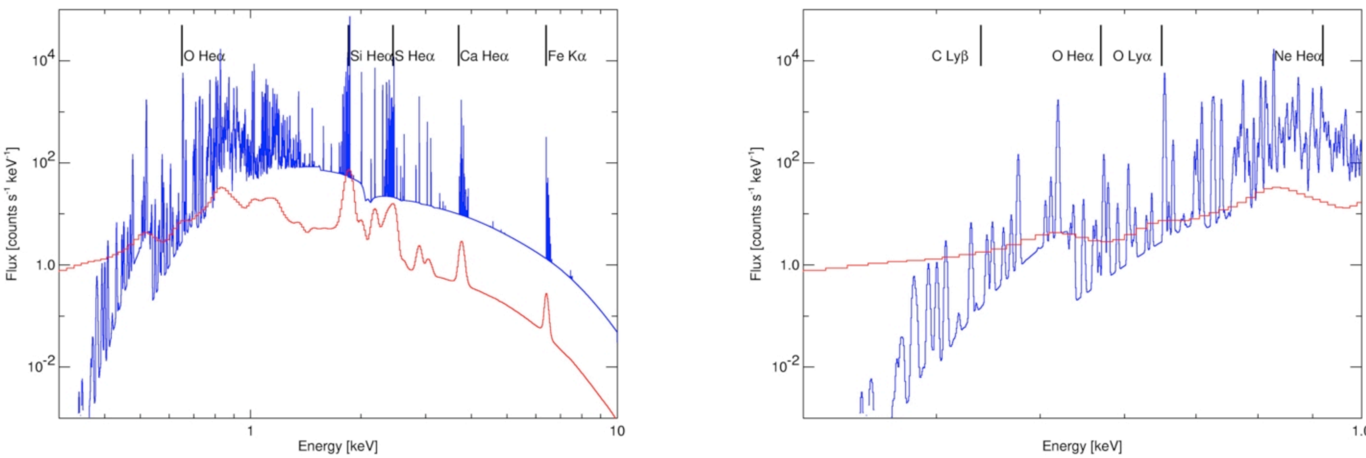


Figure 2: Simulated X-ray spectra, based on a model of Badenes et al. (2003), of the ejecta emission from Tycho's SNR convolved with the XMM EPIC-MOS (red) and Con-X XRS (blue) response functions. The left panel shows the entire band from 0.3-10 keV and the right panel shows an expanded view of the low energy region. Prominent line features from several abundant elements in the ejecta are noted.

Probing Cosmic Ray Acceleration in Supernova Remnants

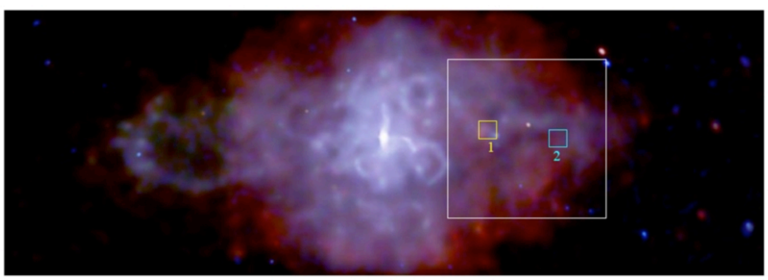
The presence of non-thermal X-ray emission in shell-type SNRs confirmed that such remnants are sites of high-energy particle acceleration that are part of the cosmic-ray spectrum. Assuming typical magnetic fields, the radio and X-ray properties of several young SNRs indicate the presence of electrons with energies of 10-50 TeV, which still falls far short of the "knee" in the cosmic-ray spectrum at an energy of >~1000. Moreover, while the total cosmic ray energy density is dominated by ions, only the emission from electrons is directly observed in X-rays. Two key questions arise: What are the maximum energies available from particle acceleration in SNRs? Is there evidence for hadron acceleration in SNR shocks?

Hadron acceleration by SNR shocks can be identified through dynamical effects. For a given shock velocity, strong cosmic-ray acceleration will yield a lower-than-expected temperature than if the full shock energy heated the gas. Crucial X-ray measurements, then, are the temperature and velocity of the shocked gas. Using Chandra observations, Hughes, Rakowski, & Decourchelle (2000) found the electron temperature of the forward shock in SNR E0102.2_7219 was significantly lower than the temperature inferred from the remnant's expansion velocity. This led them to argue for the presence of strong cosmic-ray acceleration. A large effective area and high spectral resolution are required to characterize gas in SNRs with primarily non-thermal X-ray emission (e.g. G347.3–0.5). The spectral resolution provided by the Constellation-X calorimeter will allow detection of thermal broadening, or a centroid shift, associated with the expanding shock for velocities >~600 km s^{-1}. Line ratios will establish the temperature of the X-ray emitting gas. In addition, comparisons of the shock velocity (i.e. from the ions) with the electron temperature will reveal the shock-energy fraction used in particle acceleration, thus identifying the hadronic component of the particles.

Pulsars and Their Wind Nebulae

Pulsars are the most extreme form of matter short of black holes. Their ultra-high densities, rapid rotations, and strong magnetic fields carry imprints of their formation processes in core-collapse SN. As they age pulsars spin down, depositing vast amounts of energy into their surroundings through relativistic winds and, in some cases, jets. Key elements of their evolutionary history are revealed by these wind nebulae and the properties of the ejecta they sweep up.

Of particular importance are "naked" pulsar wind nebulae (PWNe) like the Crab Nebula and 3C 58, which exhibit little or no evidence of ejecta or material swept up by the SNR blast wave. This lack of observed thermal emission implies that they are expanding into extremely rarefied surroundings. However, ejecta must have formed in the explosion. A large collecting area and high spectral resolution in the soft X-ray band are needed to detect and characterize this gas. Chandra studies of low-energy emission in the outer portions of the 3C 58 PWN reveal thermal gas overabundant in Ne and Mg. The nebula itself is believed to have formed in a supernova event from 1181 CE, and a rapidly-rotating neutron star is located at its center. However, the size of the PWN (9.3 pc by 5.6 pc assuming a distance of 3.2 kpc) requires average expansion velocities of >~ 10,000 km s^{-1}, while the highest velocities measured are of order 900 km s^{-1}. Identification of the higher-velocity gas is crucial to understand how this nebula has evolved.



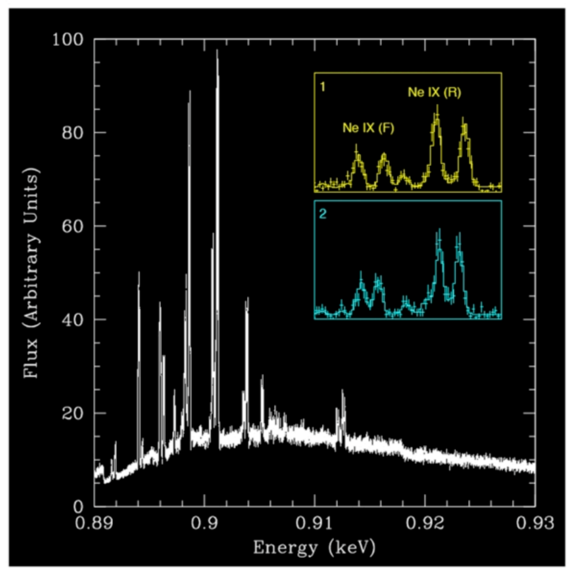


Figure 3: (*left*): *Chandra* image of 3C 58 with the Constellation-X calorimeter field of view (white) and two 15"× 15" extraction regions indicated. *(right):* Simulated spectra of the entire region (white) and the Ne IX (helium-like) K line complex from the two smaller regions (yellow and cyan, corresponding to the colored extraction regions). The two-component spectrum observed with *Chandra* is assumed, with a power law accompanied by a thermal spectrum assumed to originate in a shell. The expansion velocity of the shell is assumed to be 900 km s^{-1}, as observed in optical laments. The Doppler-shifted features from the front and back shells are clearly separated, and the variation in the projected velocity with radius is also evident as a smaller separation between the lines in the western-most (cyan)

Based on Chandra observations, a 100 ks Constellation-X observation of the western region of 3C 58 will yield a surface brightness of 7×10^{-3} cts ks^{-1} $arcsec^{-2}$ in the Ne IX triplet. With Constellation-X's nominal 2-eV spectral resolution, velocities as low as ~600 km s^{-1} can be resolved which can easily be measured with roughly 100 counts in the line. This will allow the ejecta expansion to be measured on 10"-15" scales. Using line ratios, the temperature and ionization state of the gas can also be determined and the density estimated. These measurements will establish the expansion profile of the ejecta, and provide constraints on the wind of the progenitor star.

II. STUDIES OF THE INTERSTELLAR MEDIUM WITH CON-X

Studying the interstellar medium (ISM) of galaxies is a vital component in understanding the evolution of galaxies. Stars form from cold ISM, evolve, and may end their lives as SNe. SNe produce heavy elements, distributing them into the ISM as hot plasma, which emits radiation observed from radio to X-rays as it expands and evolves. Eventually the plasma cools, coalesces into clouds and the process begins again.

Dust and Gas in the Interstellar Medium

The composition and physical state of the ISM reflects the overall star formation properties of the Milky Way (past and present), but quantitative understanding of ISM properties remains poor. Traditional observational techniques are restrictive: mm lines trace only specific molecular species, IR continuum emission shows only blackbody radiation, and optical/UV extinction curves do not respond strongly to specific properties of individual ISM components. Further, it is difficult to combine these to learn, for example, the total carbon abundance of the ISM (cf., Dwek 1997, Zubko et al. 2004).

Soft X-ray absorption spectroscopy is the only technique sensitive to *all* ISM constituents simultaneously, including dust and all molecular and atomic species. In the soft X-ray band, the K shell absorption spectra of the elements C through Si are located between 0.28 and 1.8 keV, and the L shell spectrum of Fe is near 800 eV. For typical values of the Galactic column density, 10^{20} - 3×10^{21} cm^{-2}, the opacity at the photoelectric edges makes them readily detectable in a bright high-resolution spectrum.

In response to small changes in the valence shell (ionization, chemical binding), the photoelectric absorption edges and lines exhibit small shifts, typically on the order of a few eV. A single sensitive X-ray absorption spectrum with a few eV-resolution can therefore address all of the physical chemistry of the major constituents of the ISM. In addition, the absorption spectrum is sensitive to the presence of dust by scattering the photoelectron wave function from photons just slightly above the ionization threshold, producing a characteristic 'undulation' in the continuum absorption spectrum. This effect is also sensitive to the precise crystalline composition and structure of the absorbing material. X-ray absorption spectroscopy can therefore provide unique information on the physical properties of astrophysical dust that cannot be obtained in any other way.

Vuong et al. (2003) used low-resolution, CCD-type spectra of heavily absorbed X-ray sources to compare total metal columns with optical/IR dust extinction in molecular clouds, thus providing a reliable measure of the gas-to-dust ratio in the cold ISM. The 20% discrepancy they found was attributed to a recently-recognized error in solar abundances. This work is being extended with the Chandra Orion Ultradeep Project, which hopes to detect the depletion of ices onto grains in cold dense cores.

The validity of absorption spectroscopy has been successfully demonstrated with high resolution grating spectra of selected bright sources with Chandra and XMM-Newton. High-signal high-resolution X-ray spectroscopy showing individual absorption edges can give precision *total* abundances of individual elements (e.g., Crab pulsar, Weisskopf et al. 2004). The increased sensitivity of Constellation-X will extend this work to a larger number of lines-of-sight, and will allow more finely detailed studies of subtle features in the brightest objects.

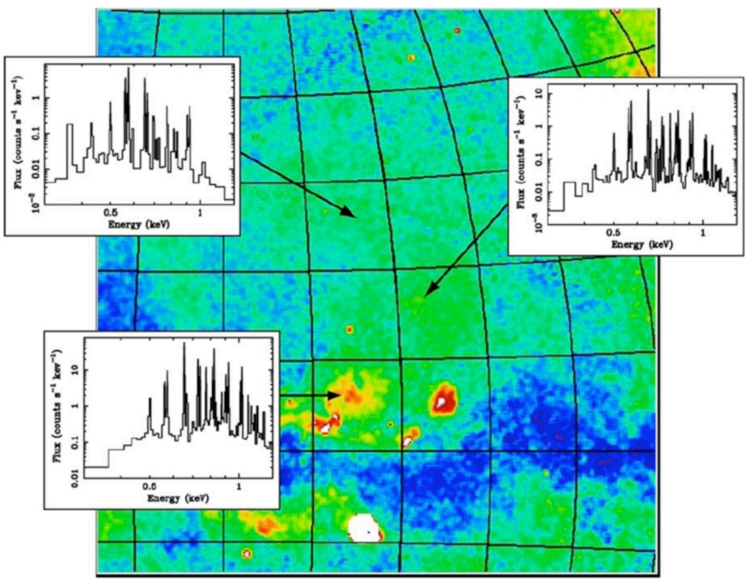


Figure 4: Chimneys connecting the galactic plane to the halo in spiral galaxies provide a mechanism for hot plasma with enhanced abundances to escape the disk. Such plasma, the result of supernovae and the winds of massive stars, heat and enrich the halo. This figure shows a possible example of such a chimney in the Milky Way, with a trail of enhanced X-ray emission from a number of energetic regions in the plane to a plume into the lower halo. The color image shows the *ROSAT* All-Sky Survey data at 3/4 keV where red indicates high intensity and blue indicates low. Model Con-X spectra, based on the *ROSAT* data, from three points in the chimney are shown. The cooling of the plasma as it progresses out of the disk can clearly be seen by the shifting of the emission to lower energies. However, Con-X observations will allow a much deeper study than what can currently be achieved with a considerably greater sensitivity to changes in ionization structure and abundances. With this additional information greater insight into the Galactic halo environment can be achieved.

The Hot ISM of the Milky Way

The X-ray emitting plasma component of the ISM can exist for millions of years and fill voids in the cooler ISM of up to hundreds of parsecs across. The longevity of this hot plasma depends on the cooling rate, which in turn depends on its interaction with surrounding ISM, depletion of the heavier elements into grains, and possible reheating by additional supernovae or strong stellar winds. If the regions of hot plasma are large and energetic enough, they can break into a spiral galaxy's halo modifying its temperature, abundance, and ionization structure. Such chimneys can divert a significant portion of the SN's energy from the galactic disk, thus affecting the disk dynamics. The center of the Milky Way, and similar galaxies, has an X-ray "bulge," where hot plasma extends for several thousand parsecs above the galactic plane. It is not clear whether the X-ray bulge of the Milky Way is in outflow or is relatively static.

Existing studies of this plasma have relied primarily on broadband imaging of large regions or spectral analysis of limited areas with spectral resolution limited to ~50 eV in the 0.5-1.0 keV spectral range. With the nominal effective area and spectral resolution of Constellation-X, maps of temperature, ionization, and abundance structures to 1' (a few parsecs in the nearby Milky Way or ~15 pc in the Large Magellanic Cloud) will be possible. In addition, it will be possible to map transition regions in detail and test for outflow in galactic chimneys and search for enhanced or anomalous abundances.

At the center of the Milky Way resides a supermassive black hole (SMBH) with a mass of 2.6 x 10^6 M_{Sun} coincident with the compact non-thermal radio source Sagittarius A* (Sgr A*) and surrounded by a complex of diffuse X-ray emitting and absorbing regions. The SMBH, Sgr A* and the H II region Sgr A West lie within the hot plasma in the central cavity of Sgr A East, which appears to be a SNR that may have passed through the position of the SMBH and caused a period of increased activity that ended within the past 300 yr (Bagano et al. 2003). Bright clumps of X-ray emission located on opposite sides of the Galactic plane along a line passing through the central parsec of the Galaxy suggests that Sgr A* may have experienced an earlier period of increased activity lasting several thousand years during which it expelled hot gas in a bipolar outflow oriented roughly perpendicular to the Galactic plane.

The Galactic center is a complex region with many possible studies for Constellation-X, including a potential X-ray reflection nebula Sgr B2 and a new population of hard X-ray sources discovered by Chandra. Koyama et al. (1996) proposed that the X-ray source associated with the Sgr B2 cloud may be an X-ray reflection nebula illuminated by Sgr A* during an earlier outburst where it reached an X-ray luminosity of 2×10^{39} ergs s^{-1} ($10^4\times$ higher than today). This model makes certain predictions about the X-ray line energies and the nature of the continuum emission that bear directly on the proposed scenario. Recent long Chandra observations (Muno et al. 2003) have revealed the presence of about 2000 hard faint X-ray sources (luminosities down to L_x ~10^{31} erg s^{-1}) within ~8' of the Galactic center whose nature is currently unknown. Bykov (2003) has suggested that some fraction of these hard X-ray sources might be associated with fast-moving SN ejecta fragments, which radiate both due to hot thermal post shock plasma and non-thermal particles accelerated at the bow shock. The key Constellation-X requirements for studies of Galactic diffuse emission and the Galactic center are high spectral resolution, high effective area, and low instrumental background.

III. HIGH RESOLUTION STUDIES OF THE INTERGALACTIC MEDIUM

According to the standard cosmological model, the Universe consists primarily of dark matter (25%) and dark energy (70%), with a smattering of (5%) of normal matter known as 'baryons'. While particle physicists define a 'baryon' as a three-quark, sub-atomic particle, (e.g. protons and neutrons), astronomers define baryons as ordinary matter (H, He and heavier elements) that forms planets, stars, galaxies, and gas in space.

UV and X-ray spectroscopic measurements suggest that many of the missing baryons lie in low-density gas distributed throughout the intergalactic medium (IGM), where it has not yet coalesced into galaxies, but these reservoirs of intergalactic gas (HI and O VI) still leave 40-45% of the baryonic matter missing. Cosmological simulations suggest another source of missing matter, predicting that 30-40% of the baryons reside in ~10^6K gas shock-heated by gravitational collapse and galactic outflows driven by SN. At these high temperatures, low-density gas is nearly invisible in the optical; however, heavy elements such as O, N and Ne retain a few bound electrons detectable by absorption lines in the UV (O VI) and soft X-ray (O VII and O VIII).

From theoretical simulations (e.g., Cen & Ostriker 1999; Dave et al. 2001) of large-scale structure and cosmological hydrodynamics, the IGM gas is expected to exhibit a filamentary network shaped by gravitational collapse, shock-heating, and photoionization by QSOs. Spectroscopic studies with Hubble Space Telescope and FUSE confirm this picture of the low-z "Lyman-α forest" (Penton, Shull, & Stocke 2000; Tripp, Savage, & Jenkins 2000). To measure the hot (shocked) phase of the IGM in the X-ray resonance lines of O VII (21.6019 Å) and O VIII (18.9689 Å), one requires both sensitivity and spectral resolution consistent with the absorption structures seen in Lyα and O VI. For these lines, HST and FUSE studies show velocity two-point correlations at the level (ΔV) < 200 km s^{-1} (Penton et al. 2000). Absorption studies of H I, O VI, and O VIII with FUSE, HST, and Chandra (Shull et al. 2002; Fang et al. 2002) suggest that the optimal resolution required is ~100 km s^{-1} (R = 3000) to identify and separate kinematically the IGM absorbers. To some extent increased effective area can compensate for reduced resolution, but below a value of R ~1000 the resolution is getting near the limit of solving the kinematic ID problems.

IV. TECHNICAL REQUIREMENTS FOR CONSTELLATION-X

The most important instrumental performance characteristic for this subject area considered in its entirety is the point-spread-function (PSF) of the telescope, which should be 5" or less. The most important studies that require this PSF value include the ejecta knots in Cas A, SNRs in the Magellanic Clouds and beyond, point source removal in diffuse Galactic emission, and faint sources near the Galactic center. Some studies of larger SNRs (e.g., Tycho and SN1006) would yield valuable results with a PSF of 10"-15", but a better PSF would result in better science.

Next in importance is spectral resolution, which for the non-dispersive device should be <2 eV below 8 keV. At the oxygen K lines this corresponds to a velocity resolution of ~1000 km s^{-1}. The prime science is to measure velocities and line broadening as detailed in several studies above. Higher resolution for the dispersive spectrometer (R ~ 3000) is optimal for studies of absorption in the ISM/IGM, although much good science could be done with lower R if the effective area were increased to compensate. The non-X-ray background needs to be kept at or below the level of the unresolved cosmic X-ray background. Below E = 1.5 keV this is driven by the science of diffuse Galactic emission; above E = 1.5 keV the requirement is driven by measuring abundances in SNRs and studying the faint diffuse emission in the Galaxy and MC.

The nominal effective area of the Constellation-X baseline is sufficient to study SNRs in M31 and M33; it would need to be increased significantly (to something like the XEUS baseline) to study remnants in the more distant galaxies M81 and M101. Soft Galactic X-ray background studies would benefit from increased effective area below 0.5 keV to a level of 500 cm^2.

One requirement on the FOV of the high-resolution non-dispersive spectrometer is that it needs to be large enough that local background can be accurately subtracted from unresolved targets. From very simple general considerations it can be shown that one gets to 90% of the optimal signal-to-noise ratio when the area for background estimation is roughly 3× larger than the source extraction area. Having a larger FOV device with lower spectral resolution (e.g., CCD-type) would not be particularly valuable for this subject area. FOV should not be increased at the expense of effective area, since many studies can be done by raster scanning or mosaicing over a large extended target. This capability must be available to observers and it should be possible to execute such observations efficiently, i.e., with minimum setup or other overheads.

Our high count rate capability requirement is 3000 cts s^{-1}, which corresponds to a 2.5' square region of a bright portion of Cas A. Constellation-X follow-up studies of supernova and other transient events require rapid response (<~2 days, based on SN Ia studies), and the ability to slew at any one time to a large fraction of the celestial sphere. If the sky coverage is 50% then Constellation-X will be able to target 2 SNe Ia over the course of a 5-yr mission. If the coverage drops to 10%, then on average it will be possible to target only 0.4 SN Ia by Constellation-X and this science is lost.

Event timing accuracy of 100μs for all instruments should be adequate for pulsar timing studies. For the hard X-ray telescope, extending the upper end of the energy band to beyond 78 keV would allow the study of nuclear transition lines from radioactive ^{44}Ti in young Galactic SNRs. Angular resolution of 1' is probably acceptable for this instrument and it should have a FOV no less than that of the soft X-ray telescope.

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